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Searching for Jets in Asymmetrical Nebulae with the Hubble Space Telescope

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Abstract. The jets seen in NGC 6543 motivated us to search for similar features in other PNe. Our HST snapshot program looked for jets using the [N II] and Hα narrow-band filters. Although spectacular jets are found in proto-PNe, true jets seem rare among mature PNe. In the later group, IC 4593 is the best case in our sample. We distinguish between jets and a number of interesting "jet-like" features, e.g., "cometary" structures with a dense globule at the end facing the central star.

1. Introduction

Observations of Herbig-Haro objects like HH30 and HH34 have provided perhaps the best images of narrow, continuous jets. These jets are known to originate in the accretion disks surrounding the associated T-Tauri stars. Recently, morphological studies of PNe have revealed many "point-symmetric" structures, which would have a natural explanation if the nebula were once subjected to the effects of precessing jets. But the existence of jets seems at variance with the conventional picture of the PN central star, which does not involve an accretion disk. In this context, any observations of jets in PNe, which provide a more direct indication of stellar accretion disks, are especially interesting.

HST observations of NGC 6543 (the "Cat's Eye Nebula") confirmed the earlier indications (Miranda & Solf 1992) of a remarkable pair of jets in this object (Figure 1). We wanted to see if similar structures exist in other PNe. With this in mind, we carried out a "snapshot" imaging program of likely nebulae with the HST.

2. The HST Snapshot Program

We selected our targets based on three criteria: (1) reports of high velocity flows (e.g., He 3-1475, the Eskimo), (2) point-symmetric morphologies, (3) ground-based images that showed "jet-like" structures. Since we found that in the case of NGC 6543 the jets were best seen in the ratio of the [N II] λ6584 to Hα filter images (Figure 1 is such a ratio image), we requested [N II] and Hα images

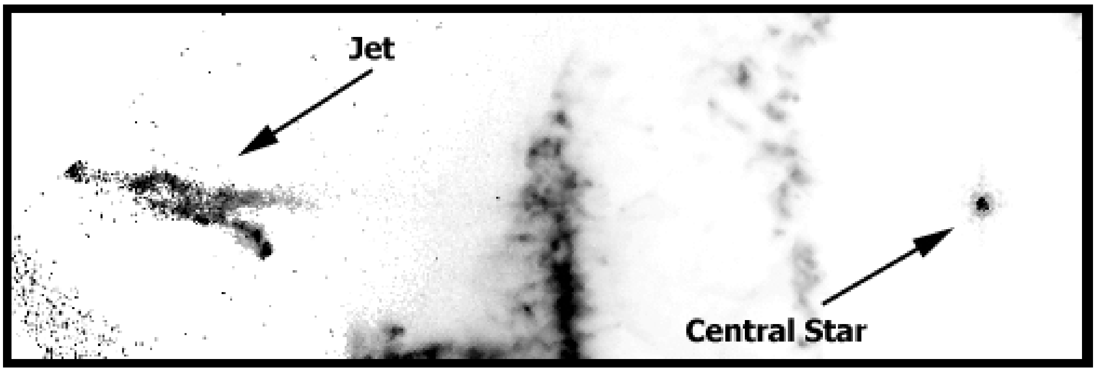

Figure 1. One of the pair of jets in NCG 6543.

Table 1. Targets Observed in Snapshot Program No. 6347

	HST Name	Other Name(s)	Filter(s)	Comments
1	PK190-17D1	J 320	Hα	multi-polar
2	PK242-11D1	M 3-1	[N II], Hα	large point-symmetric PN
3	NGC2392	PK197+17D1, Eskimo	[N II], Hα	cometary tails
4	IC4593	PK025+40D1	[N II], Hα	bullets and jets
5	NGC6210	PK043+37D1	[N II]	one bullet
6	PK336-05D1	He 2-186	[N II]	isolated bi-knots
7	PK003+02D1	Hb 4	[N II], Hα	corkscrew jets, not aligned
8	He 3-1475	IRAS 17423-1755	[N II]	high velocity, conical jets
9	PK032+07D2	PC 19	[N II]	spiral! (point symmetry)
10	PK051+09D1	Hu 2-1	[N II], Hα	twisting axis
11	PK032-02D1	M 1-66	Hα	conical structures
12	PK055+02D2	He 1-1	Hα	radial streaks
13	M1-92	(Minkowski's footprint)	[N II]	PPN with bipolar outflow
14	NGC6881	PK074+02D1	[N II], Hα	huge bipolar

Figure 2. The "bullets" and associated bow shocks in IC 4593.

of our targets. Snapshot programs limit the exposure time; all our images are 10 minute exposures. When the program ended on 29 June 1999, 14 objects had been observed, most in [N II], but only 6 in both filters. The nebulae we observed are listed in Table 1. Since the program was basically a morphological survey, we set the public release time for our data at 2 months – all are now available from the STScI archives.

3. Results

While we have found a variety of interesting radial structures in these nebulae, we have come to the conclusion that, at least for mature PNe (as opposed to proto-PNe), real jets are rare. We consider a true jet to be a narrow, continuous, high-velocity flow. There are two types of long, radial structures which we feel have no relation to jets: we will call them *cometary structures* and *rays*. Cometary structures have a bright "head" at the end nearest the star, from which a low-ionization tail, often sinuous, extends outward. These features were first seen in the Helix over three decades ago. HST images have shown that the heads are neutral globules which are photo-evaporating. The globules are drifting outward more slowly than the surrounding ionized gas; the tails presumably result as evaporated material is dragged back by the flow. Of the nebulae imaged for this program, we found that the Eskimo has an extensive set of cometary structures. Their sinuous tails could indicate a subsonic flow past the globules. Such comets are seen in other PNe, such as NGC 6543 and A 30 (Borkowski et al. 1995). The tails may be quite long: the "jet" in NGC 7354 looks like a comet to us. There is, however, one linear feature in the Eskimo at P.A. 90° which is different: very thin, straight and directed exactly away from the star. This feature also has a clump at its head. It seems too narrow to be a jet. In NGC 6543 there is a bundle of such *rays* outside the northern cap. It seems probable that the rays are "shadow columns", where the gas, shielded from the direct stellar radiation, is ionized and heated only by the diffuse field. Such gas would be less highly ionized, cooler and hence denser. Such shadow columns might only form if the gas is sufficiently quiescent.

Our images of nebulae chosen for point-symmetry (Hu 2-1, J320, M 3-1, PC 19) show no jet-like structures, but the symmetry is seen to be much more detailed and precise than was apparent from ground-based observations. Hb-4 is a curious case. It has two jet-like structures well away from the main nebulosity, but they are not even approximately co-axial. López et al. (1997) found these structures have velocities of ± 150 km/s. We would class these features as "FLIERs". Our HST images reveal that these structures have a distinct "corkscrew" morphology; hints of similar structure are seen in the ansae of NGC 6543.

Perhaps the best case for a real jet in our sample – aside from the proto-PN discussed below – is IC 4593. Two "bullets" emerge from the main body of the nebula on an axis directly through the central star. Trails of material are seen connecting the bullets with the inner nebulosity. Several studies of this nebula have been published (e.g., Corradi et al. 1997), and it was found that the bullets have low velocities – but they may be moving nearly in the plane of the sky. Our images show: (a) that there are distinct bow-shocks around the bullets,

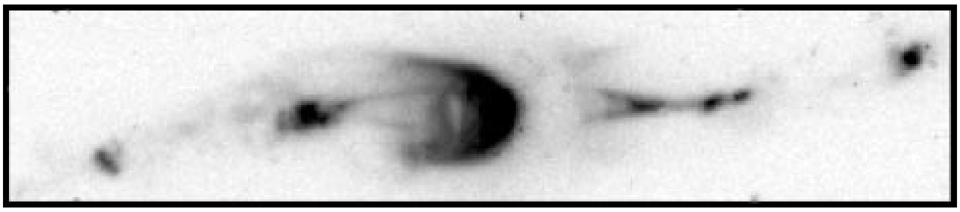

Figure 3. He 3-1475 through the HST [N II] filter.

indicative of outward motion (see Figure 2), and (b) that one of the trails/jets leads back to a conical structure in the inner nebulosity. What is curious is that, although the bullets that terminate the jets are aligned with the star, the jet leading to the conical structure shows a pronounced lack of alignment with the star. One possible explanation is that the jet which produced the trail out to the bullet has turned off, and subsequent motions of the inner nebulosity have shifted the inner part of the trail.

The type of conical structure noted in the inner part of IC 4593, which is widest near the star and narrows to an apex as we move away from the star, is also seen in other objects: M1-66, M1-92, and He 3-1475. The apex may be followed by an opening cone or outward spray. Such structures suggest flows that are being focused on a large scale – perhaps by oblique cooling shocks – rather than jets emerging from stellar accretion disks. The most spectacular object is the proto-PN He 3-1475 (Borkowski et al. 1997). It was the first object observed in our program, and we have since followed up with spectroscopic, infrared and polarization observations with Hubble's STIS, NICMOS, and FOC instruments.

The STIS results confirm the high velocities found by Riera et al. (1995). The velocity increases down the axis of the approaching jet, reaches a maximum of −970 km/s a bit before the cone apex, then declines through the apex, followed by an abrupt deceleration of over 500 km/s when the flow hits the first knot. The flow in the receding jet is similar, with a maximum velocity of +895 km/s. Though one would expect shocks at the knots to produce very high temperatures, NICMOS images show H_2 emission from the knots.

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